

*NGST Workshop*

**Electro-Active Materials for Cryogenic Actuators (20-50 K)**

**Presented by  
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## **Outline**

### **I. Electric Field Induced Strain in Insulating Materials**

### **II. Piezoelectric Materials at Cryogenic Temperatures**

#### **A. PZT-Based Ceramics**

#### **B. PZN-PT Single Crystals**

### **III. Electrostrictive Materials at Cryogenic Temperatures**

#### **A. Barium Strontium Titanate (BST)**

#### **B. Potassium Tantalate-Niobate Single Crystals (KTN)**

### **IV. Future Work**

## Sources of Electric Field Induced Strain in Insulating Materials

### A. The Piezoelectric Effect: Linear Strain vs. Electric Field in Crystals without a Center of Symmetry, e.g. Quartz

$$x_{ij} = d_{ijk} E_k$$

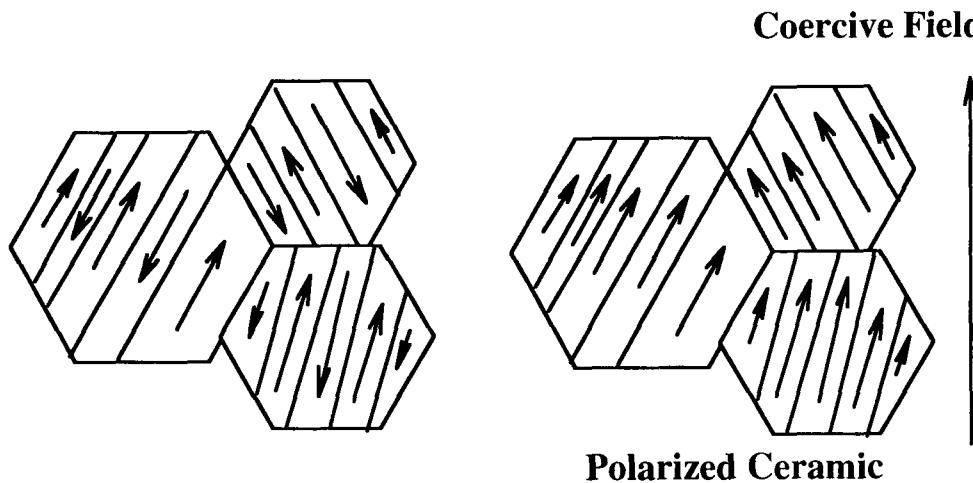
$x$  = Strain  
 $d$  = Piezoelectric Modulus  
 $E$  = Electric Field

### B. Ferroelectrics: Materials with an Electric Field Orientable Spontaneous Polarization

- Existence of Field Orientable Ferroelectric Domains (Analogous to Ferromagnetic Domains) Results in Large Piezoelectric Effect Even in Ceramics.
- Most Widely Used Piezoelectric:  $\text{Pb}(\text{Zr},\text{Ti})\text{O}_3$ -Based Ceramics
- Strain Levels ~ 0.1 to 0.2 % Depending on Material and Field (Two orders of Magnitude Greater than Quartz).

## Source of Electric Field Induced Strain Continued

- Ferroelectric Ceramics and Crystals are Made Piezoelectric by Poling: Orientation of Domains by an Electric Field



- Large Portion of Piezoelectric Effect due to Domain Wall Motion (Extrinsic Effect)
- Domain Wall Motion Tends to be "Frozen-out" at Cryogenic Temperatures

## Source of Electric Field Induced Strain Continued

### C. Electrostriction: Quadratic Dependence of Strain on Electric Field Common to ALL Insulating Materials:

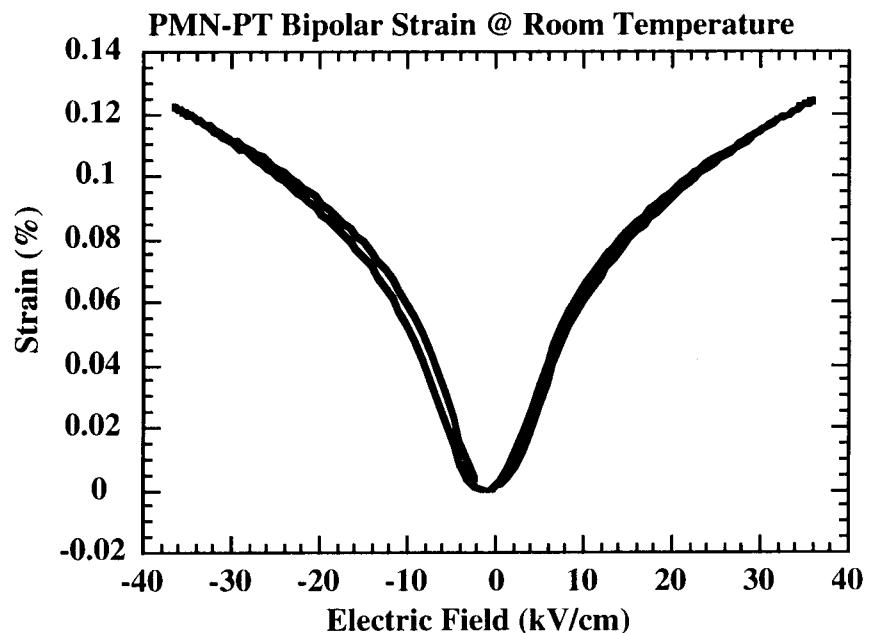
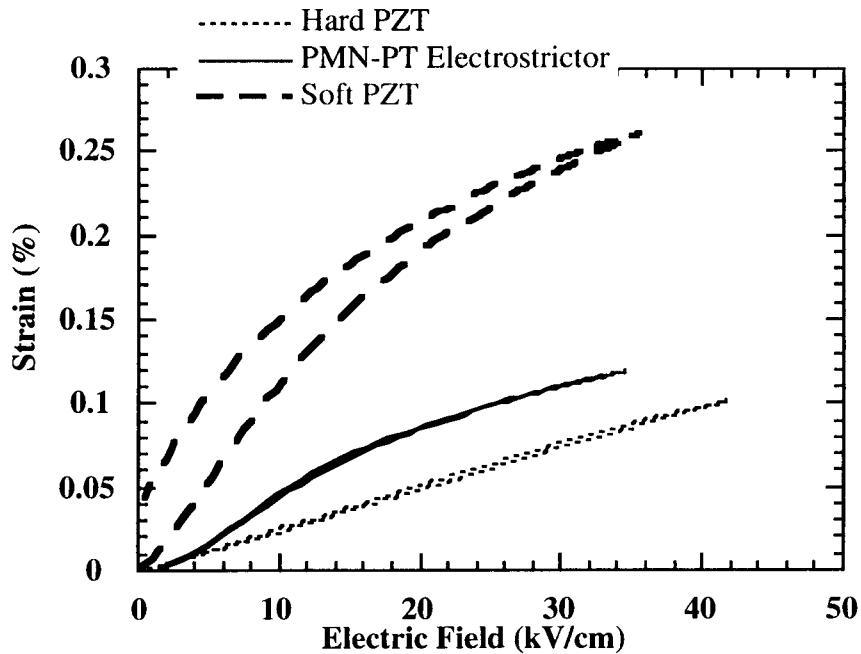
x = Strain

$$x_{ij} = Q_{ijkl} P_k P_l \quad Q = \text{Electrostriction Coefficient}$$
$$P = \text{Polarization}$$

### D. Useful Electrostrictors

- Q is Small and Varies Little from one Material to the Next
- Electrostriction has a much Stronger Dependence on Polarization
- Materials Undergoing Phase Transitions Have Anomalously Large Polarizations
- Dielectric behavior can Indicate Useful Electrostrictors  $\epsilon_r = 1 + \frac{P}{\epsilon_0 E}$
- Examples: PMN-PT, BST, KTN
- Temperature does not Effect Electrostriction. Cryogenic Electrostrictors are Simply Materials with Phase Transitions at Cryogenic Temperatures (BST)

## Comparison of Piezoelectric and Electrostrictive Strain Behavior (Room Temperature)



### Piezoelectrics (PZT):

- Broad Range of Property Engineering
- Broad Operating Temperature Range
- High Strain; High Hysteresis

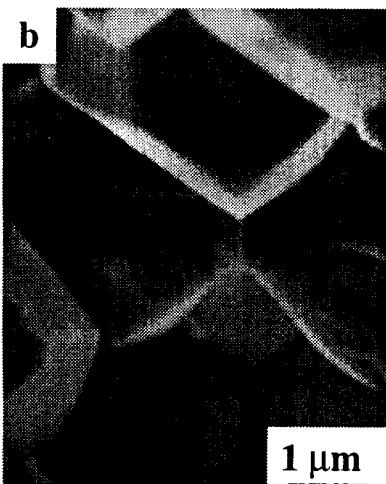
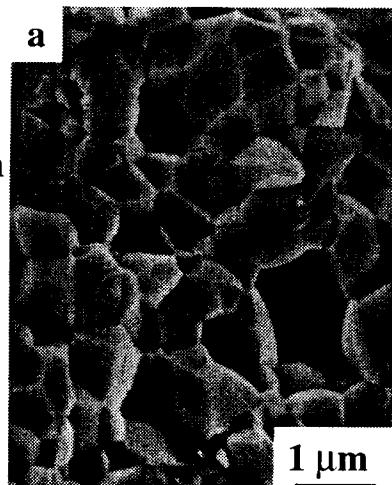
### Electrostrictors:

- Narrow Operating Temperature Range (~ 20 to 40°C)
- High Strain; Low Hysteresis

## New Developments in Electroactive Materials at TRS

**Fine Grain Ceramics ( $\sim 0.5 \mu\text{m}$ ): Reduction in Piezoelectricity Compensated by New Dopant Strategy; Clamping Effects from Grain Size Similar to Domain "Freezing" Effects at Cryogenic Temperatures.**

Fine  
Grain

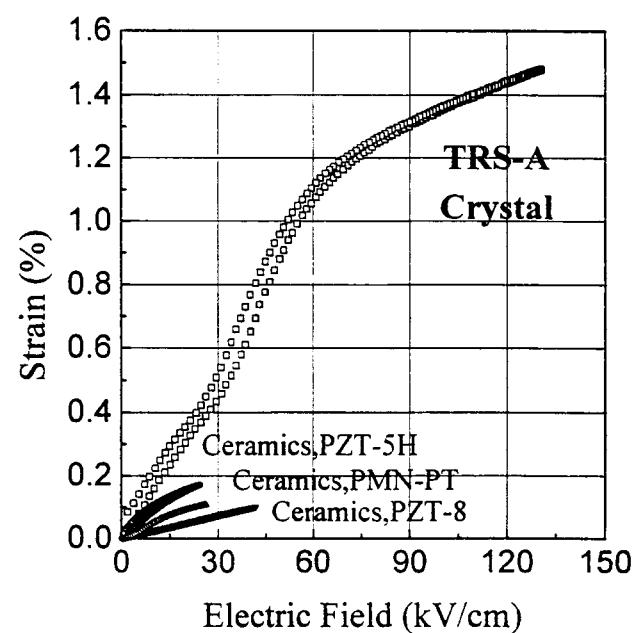
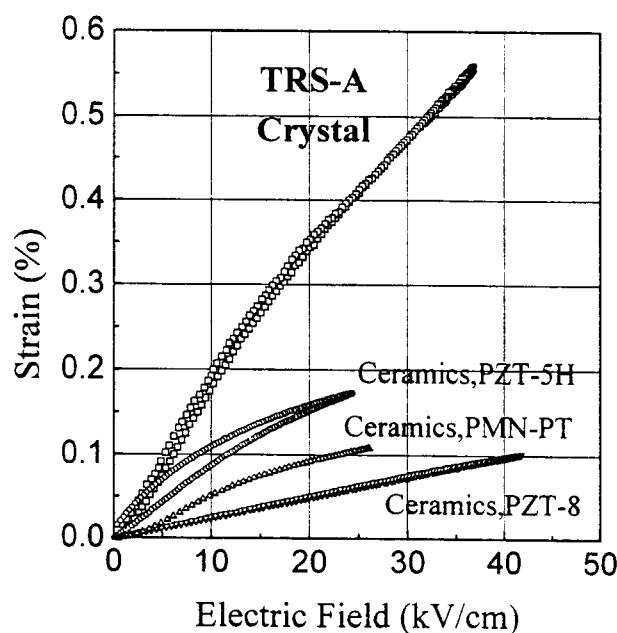
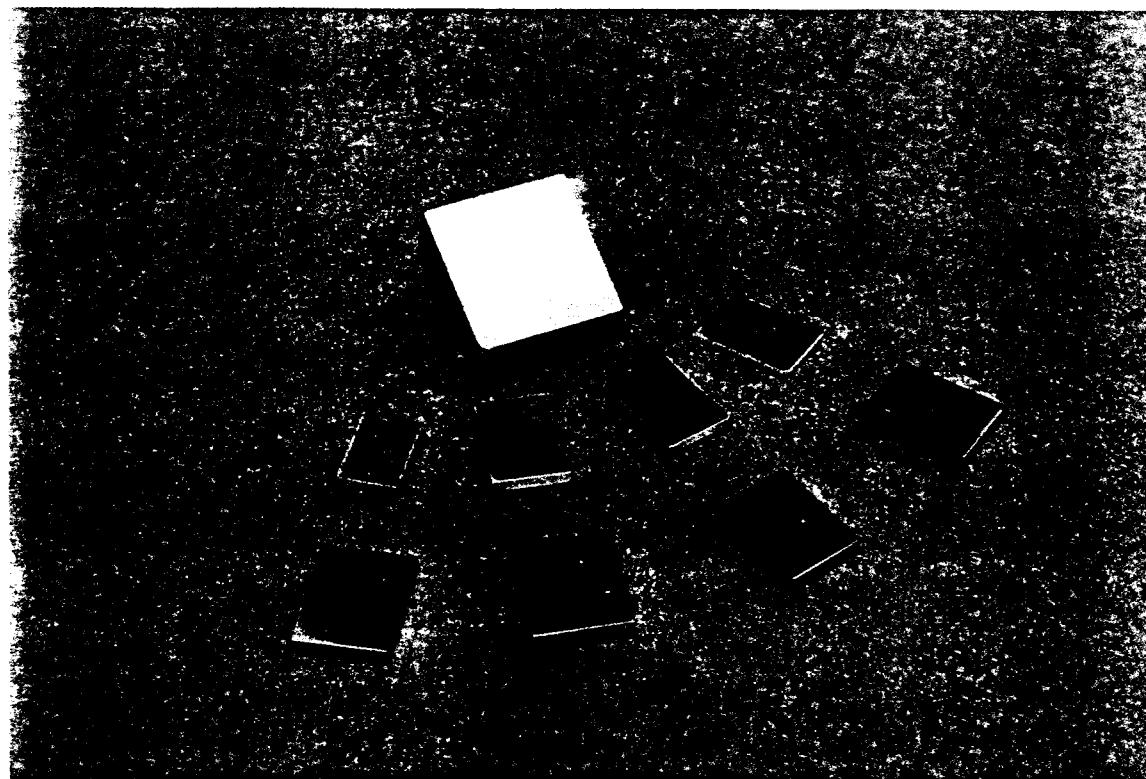


Conventional

### Advantages of Fine Grain Piezoelectrics:

- Improved Strength ( $\sim 30\%$ )
- Improved Machinability
- Thinner Layers in Stacked and Cofired Actuators for Lower Driving Voltages
- Increased Strain from Higher Electric Field Driving
- Improved Reliability from Increased Dielectric and Mechanical Strength
- Piezoelectric Properties Equivalent to Conventional PZT

# SINGLE CRYSTAL PIEZOELECTRICS



## **Development of Materials for Cryogenic Actuators**

### **1. Reformulate Soft PZT (La-doped PZT) for Increased Actuation at 30 K**

- Increase Domain Motion Enhancing Dopant Concentration (Done in Fine Grain Work)**
- Retune Zr/Ti Ratio for Morphotropic Phase Boundary Shift\***
- Drive at Higher Electric Field Using Fine Grain Ceramic**

### **2. Single Crystal Piezoelectrics: Measure PZN-PT Properties @ 30K, Reformulate?**

### **3. Electrostrictive Materials**

- BST; Tunable Phase Transition from 400 K to 0 K (Ba/Sr Ratio)**
- KTN; Extremely High Dielectric Constant @ 50 to 30 K (> 70,000)**

# Measurement of Piezoelectric/Electrostrictive Properties at Cryogenic Temperatures

## Resonance Methods:

**Impedance Spectroscopy**

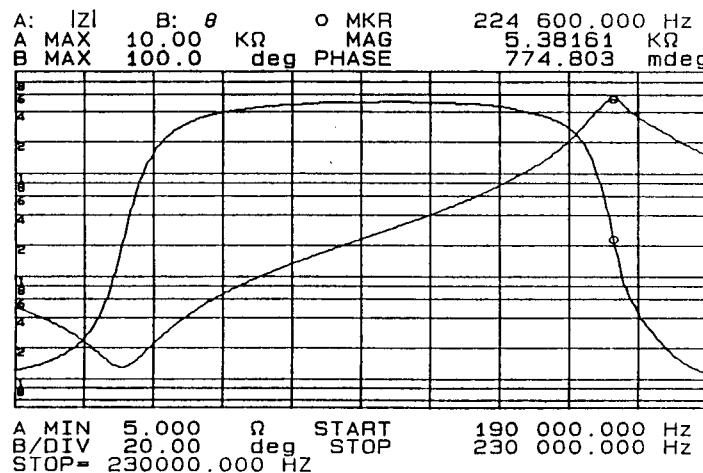
**Specific Sample Shapes Driven in Resonance by Small AC Signal ( $\pm 1V$ )**

**Frequency Limit  $> 10$  MHz**

**Measurement to 15 K**

**Piezoelectrics: Poled Ceramics or Crystals**

**Electrostrictors: AC Signal + DC Bias up to 15 kV/cm**



## Direct Inspection Methods:

**Strain Directly Measured with LVDT**

**Low Frequency ( $< 1$  Hz)**

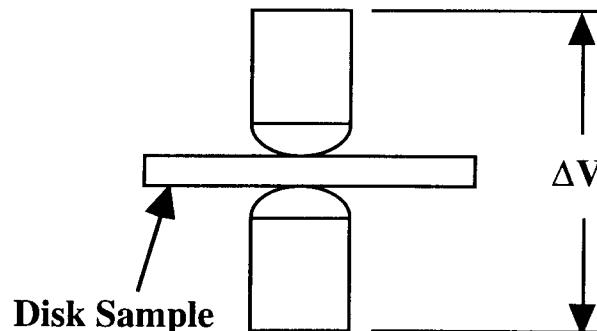
**Measurement to 77 K**

**Converse Piezoelectric Effect**

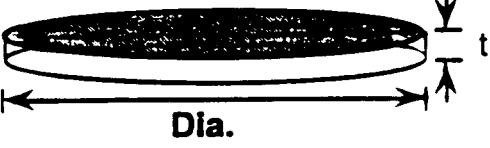
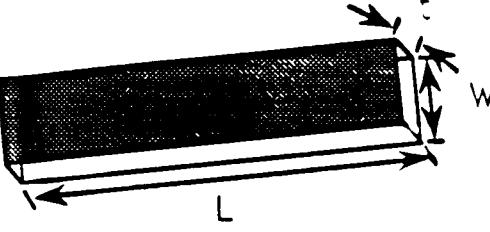
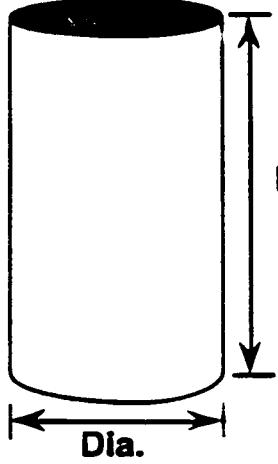
$$x = d^* E$$

$$d = dx/dE$$

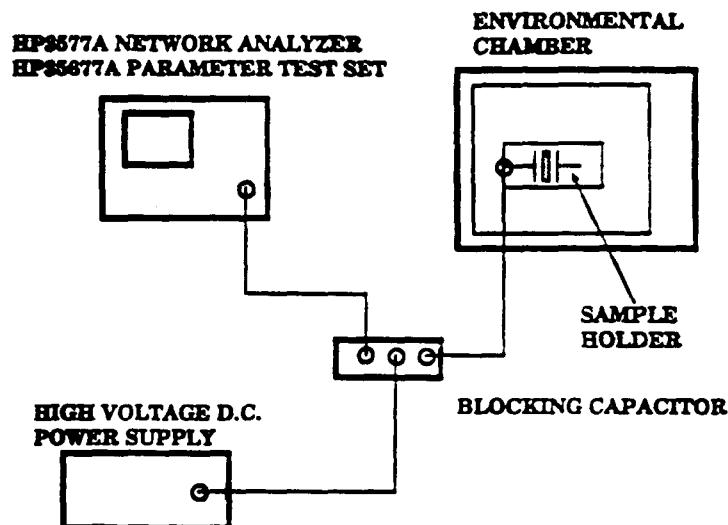
**$d_{33}$  Measurement**



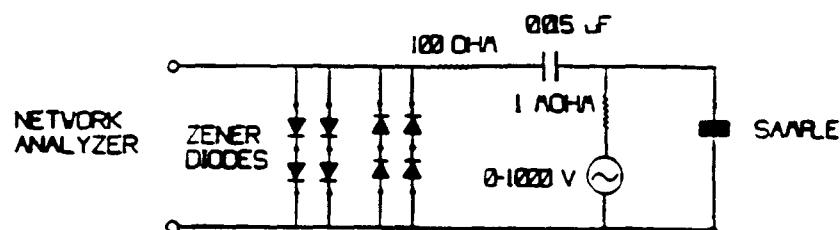
## Sample Shapes and Equations for Resonance Measurements

Sample Geometry	Coefficients	Equations
 <p>Dia.</p>	$\text{Dia.}/t \geq 30$ $K_i, \sigma, k_p$	$* K = \frac{(t)(C)}{(\epsilon_0)(A)}$ $* \sigma \sim f_{s1}/f_{s2}$ $* k_p = \left( \frac{2}{E} \right) \left( \frac{ k_{31} ^2}{1-\sigma} \right)$
 <p>L W t</p>	$L/t \geq 12$ $W/t \geq 3$ $L/W \geq 4$ $s_{11}^E, d_{31}, k_{31}$	$* s_{11}^E = \frac{1}{(\rho) \sqrt{(2L)(f_s)}}$ $* \frac{ k_{31} ^2}{1 - ( k_{31} )^2} = \frac{\pi}{2} \frac{f_p}{f_s} \tan\left(\frac{\pi}{2} \frac{\Delta f}{f_s}\right)$ $* d_{31} = k_{31} \sqrt{(\epsilon_{33}^T)(s_{11}^E)}$ $* \epsilon_{33}^T = (\epsilon_0)(K)$
 <p>L Dia.</p>	$L/\text{Dia.} \geq 2.5$ $s_{33}^E, d_{33}, k_{33}$	$* \frac{1}{D} = 4(\rho)(f_p)^2(L)^2$ $* s_{33}^E = \frac{D}{(1 - (k_{33})^2)}$ $*  k_{33} ^2 = \frac{\pi}{2} \frac{f_s}{f_p} \tan\left(\frac{\pi}{2} \frac{\Delta f}{f_p}\right)$ $* d_{33} = k_{33} \left( (\epsilon_{33}^T)(s_{33}^E) \right)^{\frac{1}{2}}$

# Resonance Measurements

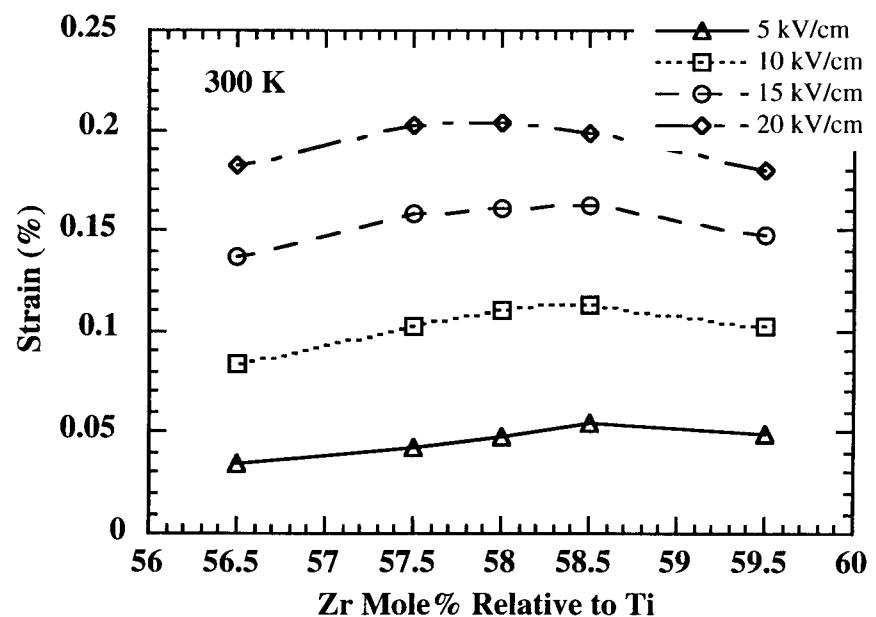
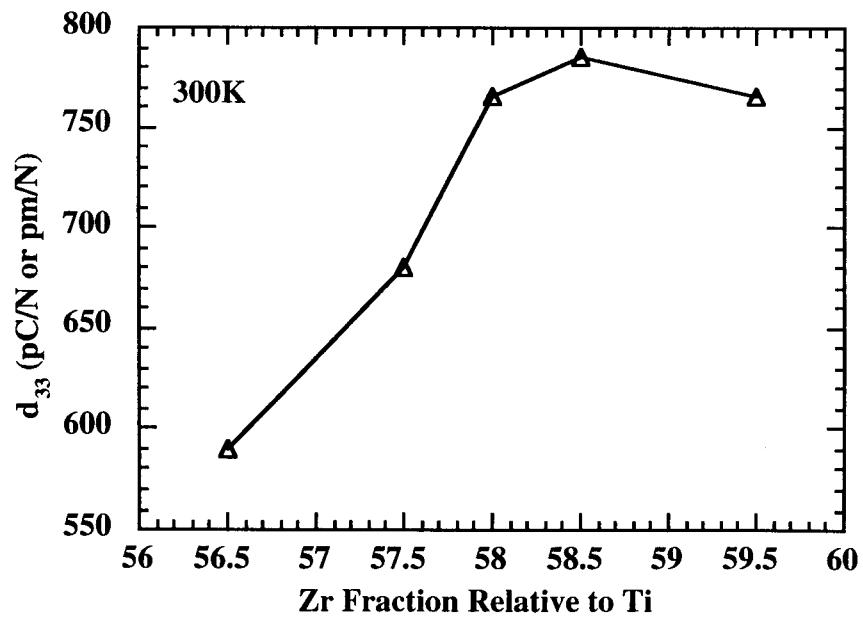
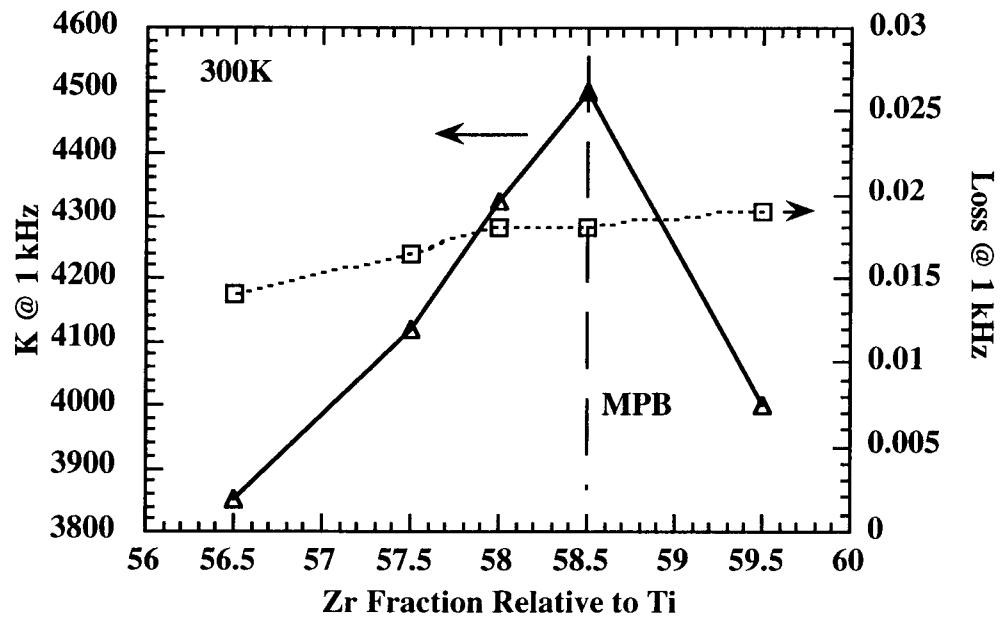
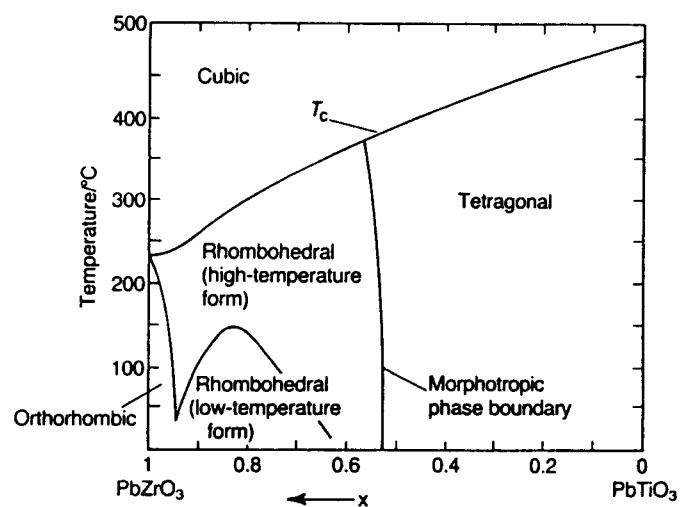


**Network Analyzer with S-Parameter Test Set**  
**Measurement based on S<sub>11</sub> (Reflection)**

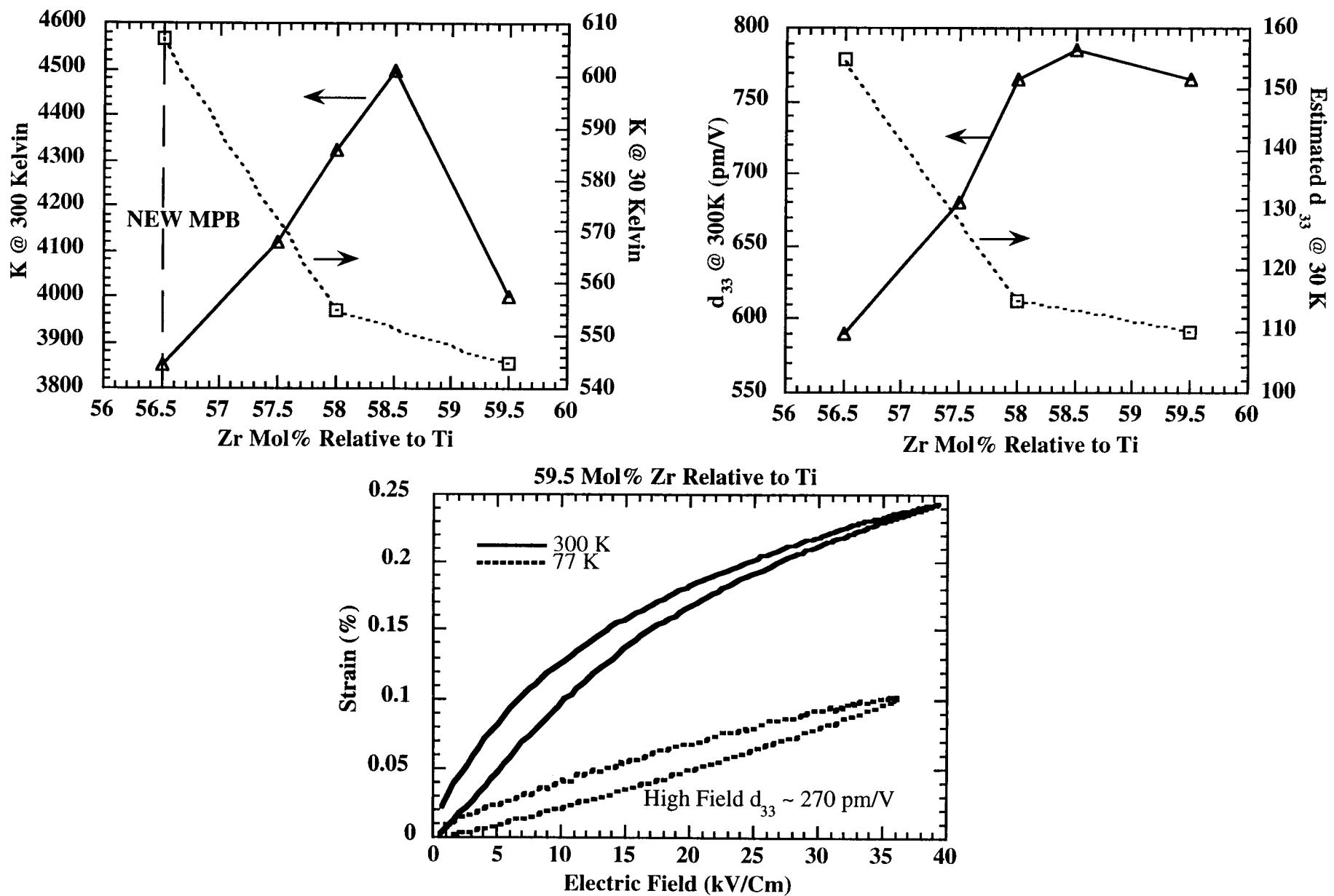


**Blocking Circuit; Maximum Frequency ~ 5 MHz; V<sub>max</sub> = 1000V**

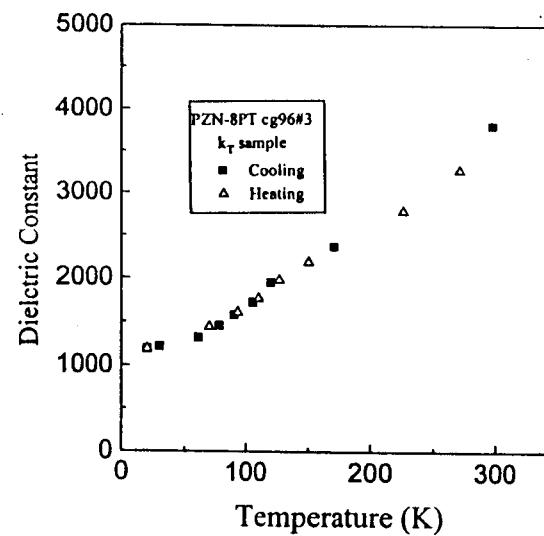
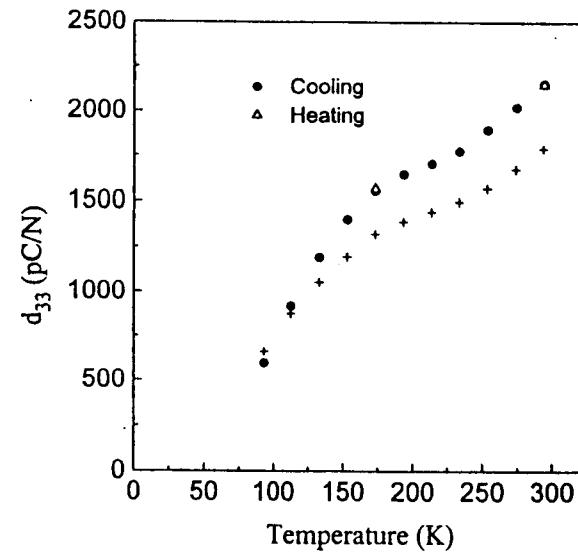
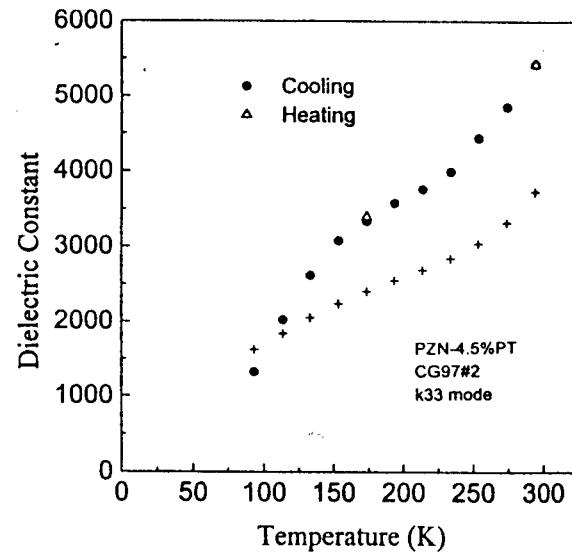
# PZT Ceramics at Cryogenic Temperatures



## PZT at Cryogenic Temperatures



## PZN-PT Single Crystals at Cryogenic Temperatures



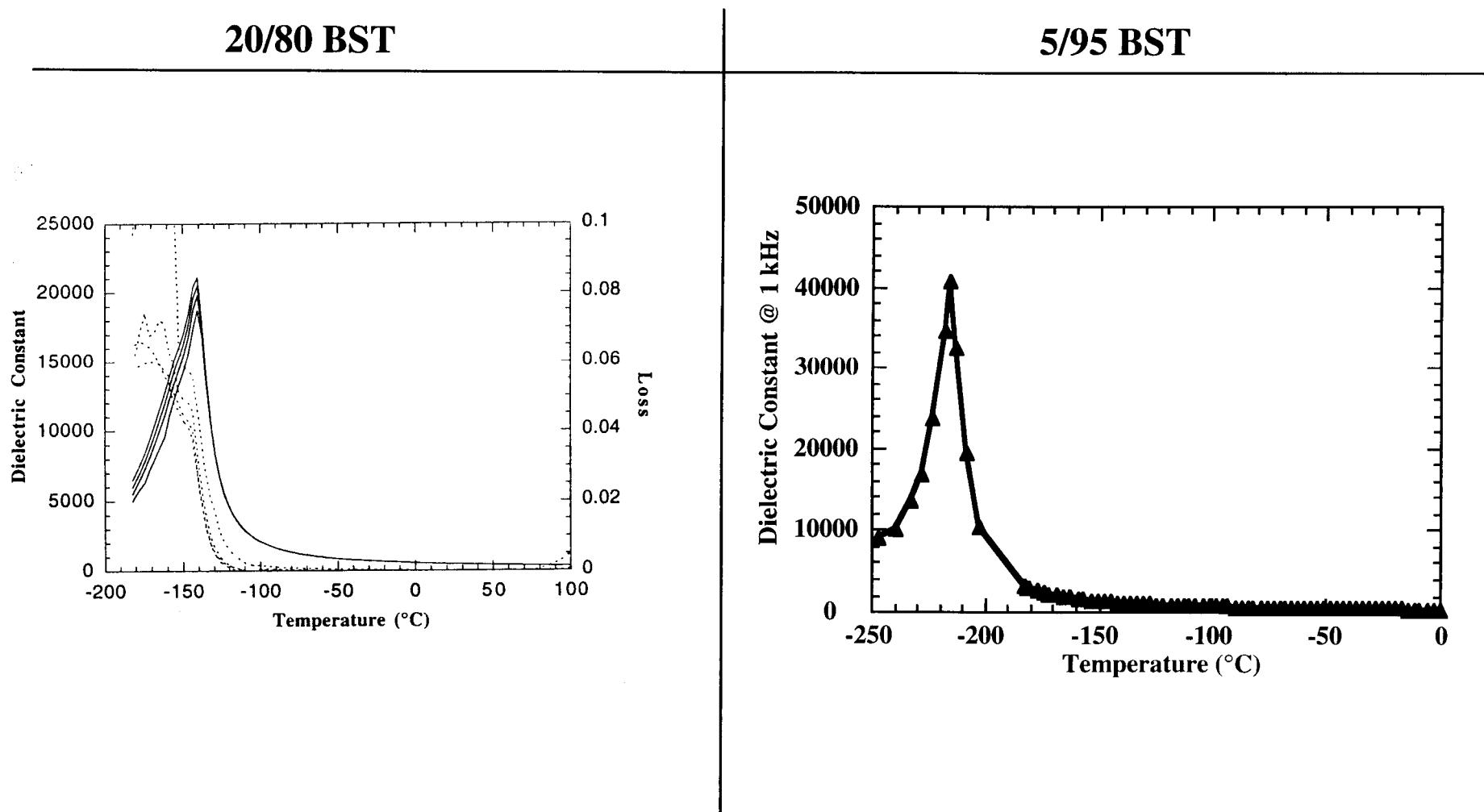
## **Summary of Piezoelectric Work**

- **Retuning PLZT Composition for Operation at 30 K Shows Promise for Providing a Usable Cryogenic Actuator Material**
- **Further MPB Tuning and Increased Dopant Levels will be Investigated to Increase the Low Field  $d_{33} > 200 \text{ pm/V}$**
- **Use of Fine Grain Material and High Field Driving ( $\sim 35 \text{ kV/cm}$ ) may Provide Strains of 0.1%, Comparable to Room Temperature Actuators.**
- **More Work Needs to be done to Determine the Cryogenic Properties of PZN-PT Crystals. Preliminary Results Suggest Low Field  $d_{33}$  of  $\sim 400 \text{ pm/V}$  may be Possible**

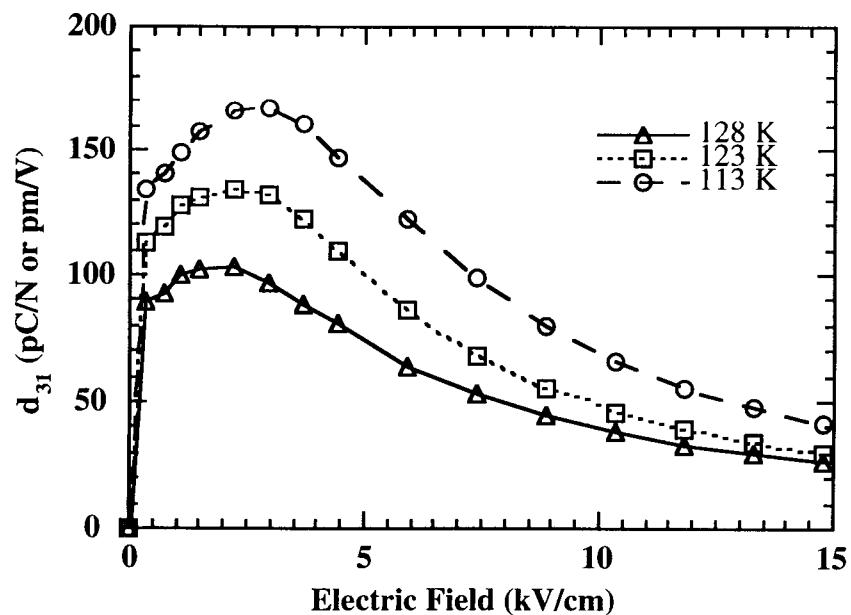
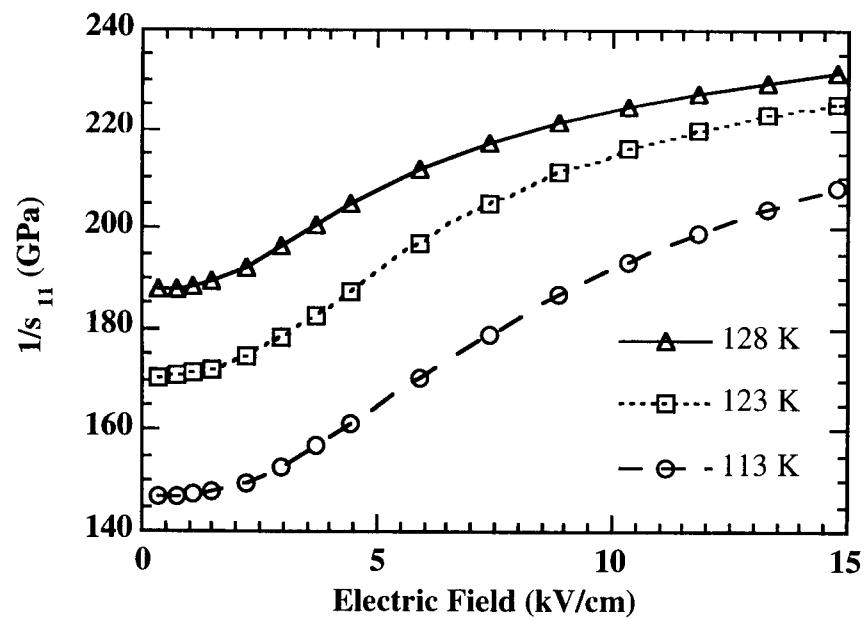
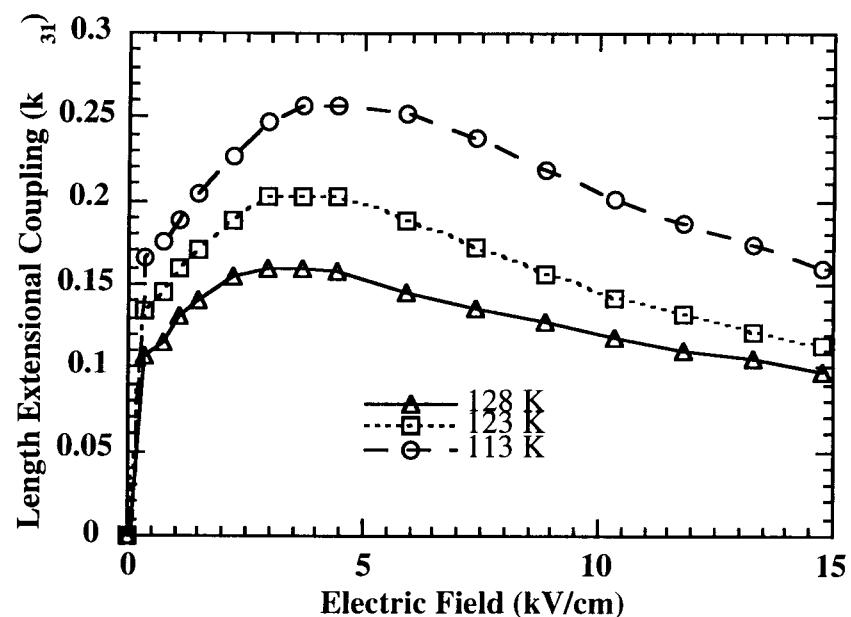
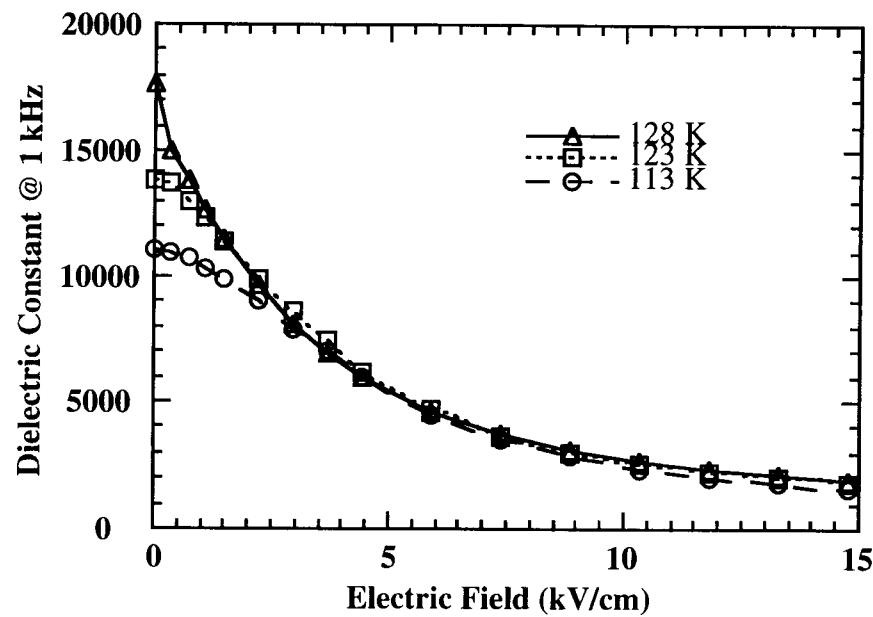
## Electrostrictive Materials at Cryogenic Temperatures

$\text{Ba}_{0.2}\text{Sr}_{0.8}\text{TiO}_3$ ;  $T_c \sim 133\text{K}$ ; Liquid  $\text{N}_2$  Measurement System

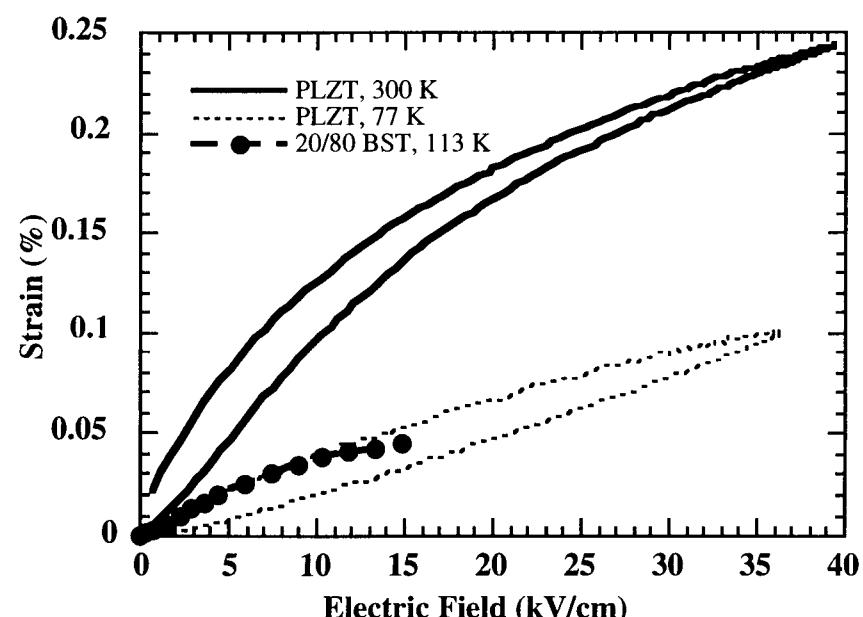
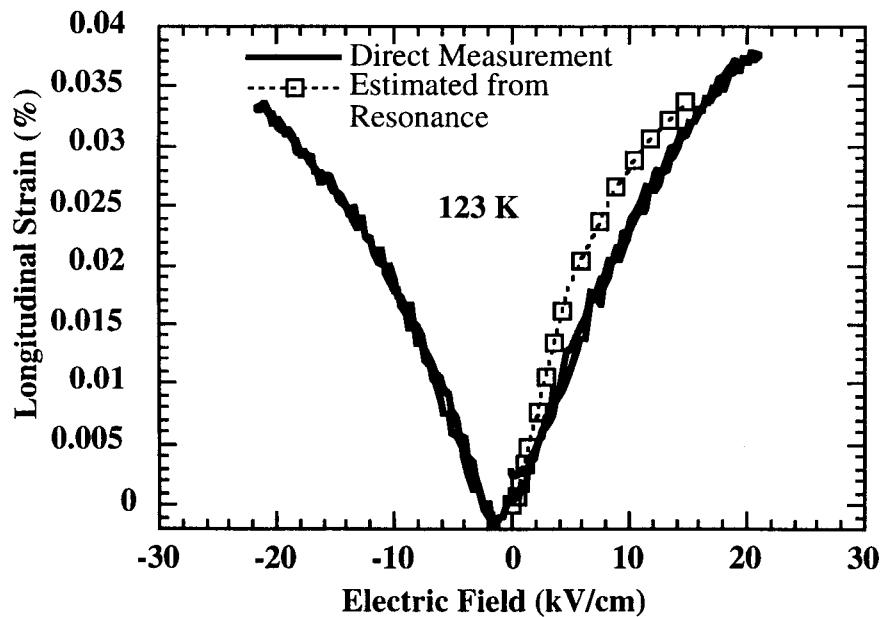
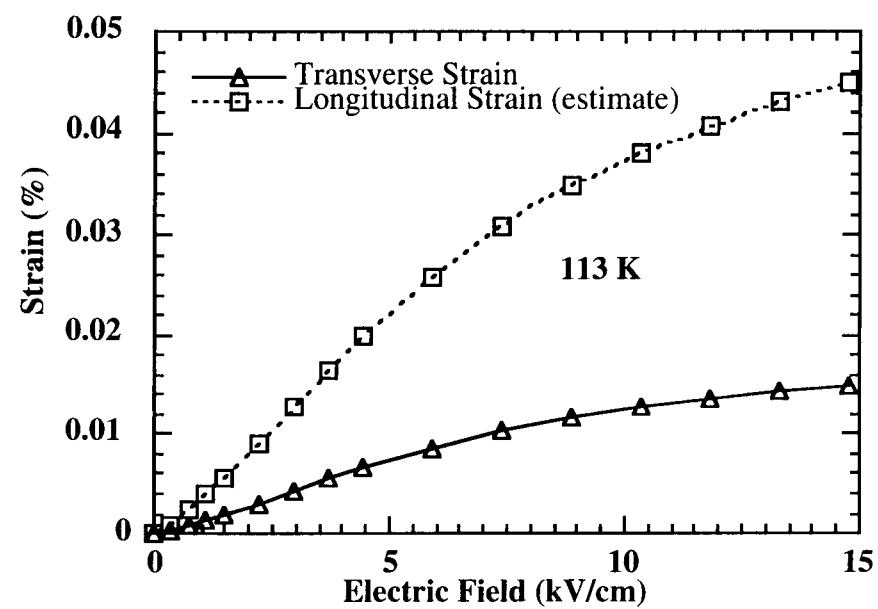
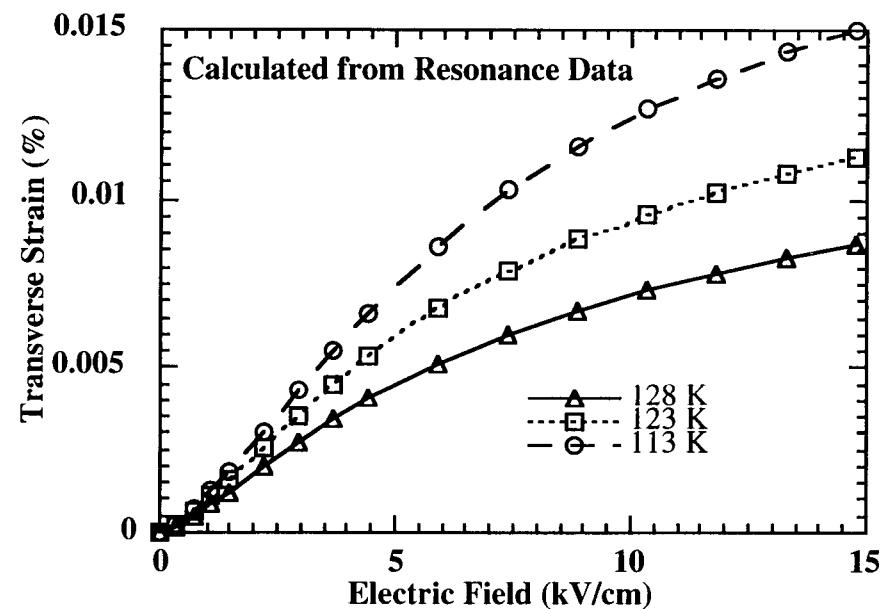
$\text{Ba}_{0.05}\text{Sr}_{0.95}\text{TiO}_3$ ;  $T_c \sim 57\text{K}$ ; Helium Cryostat



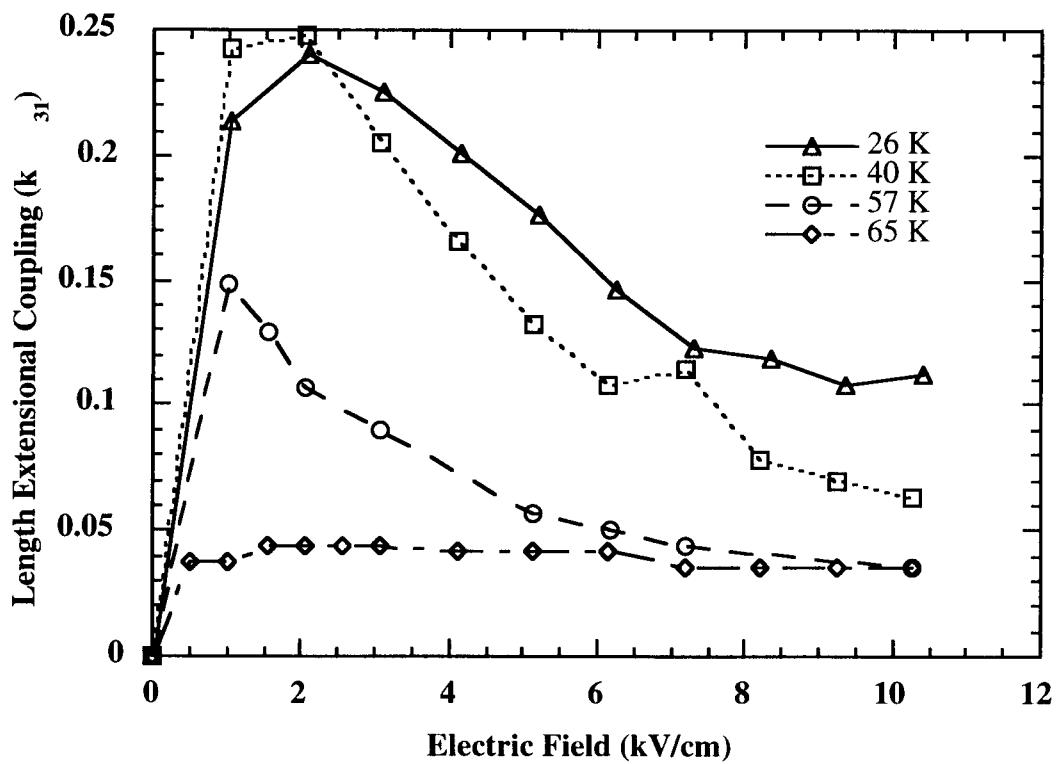
## Induced Piezoelectric Properties for 20/80 BST



## Field Induced Strain in 20/80 BST

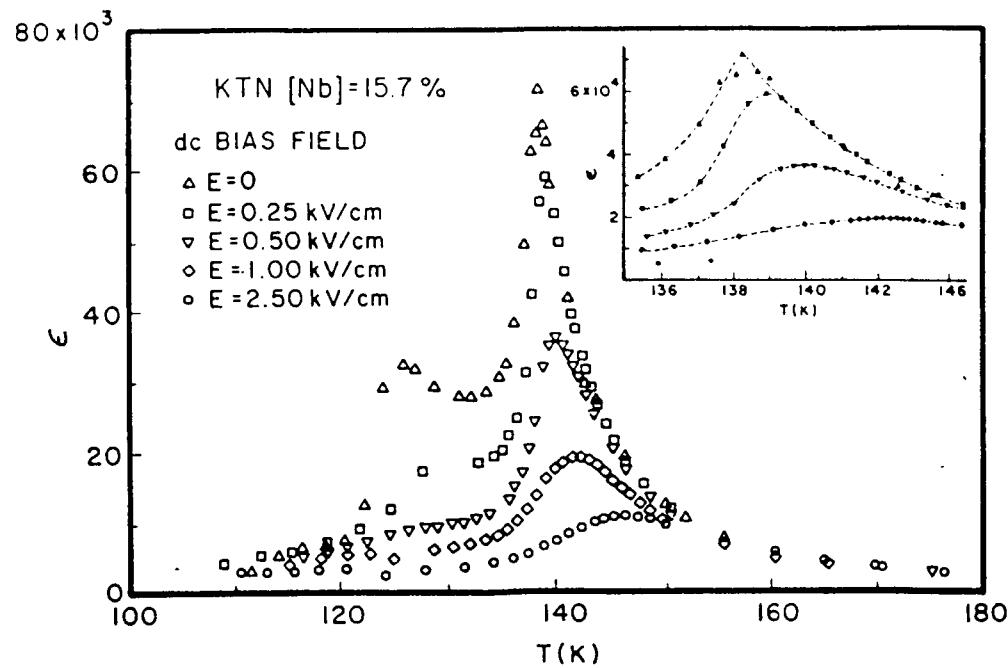


## 5/95 BST Induced Piezoelectric Properties



## KTN Single Crystals -- Super Electrostrictor ?

TOULOUSE, WANG, KNAUSS, AND BOATNER



## **Summary of Electrostrictor Work**

- **20/80 BST has Equivalent Strain to PLZT at Liquid Nitrogen Temperature**
- **Coupling Measurements on 5/95 BST Suggest it has Equivalent or Better Strain than 20/80 BST.**
- **5/95 BST is the Correct Composition for an Operating Temperature of 25 to 50 K**
- **5/95 BST is Expected to have Better Strain than PLZT at 30 K**
- **Measurements on Electrostriction in KTN Crystals were Inclusive owing to Poor Crystal Quality**

## **Future Work**

- **Complete Resonance Measurements on 5/95 BST**
- **Perform Strain Measurements with Cryostat using Strain Gauges (5/95 BST)**
- **Complete PZN-PT Resonance Measurements to 30 K**
- **Continued Compositional Tuning of PLZT to Increase  $d_{33} > 200 \text{ pm/V}$**

### **Long Term**

- **Evaluate Performance of Stacked and Cofired Actuators at 30 K**
- **Determine Merit of High Driving Field Actuators Fabricated for Fine Grain PLZT**